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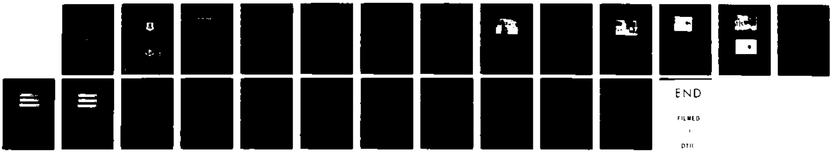

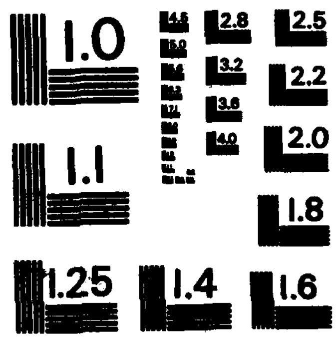

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STUDY OF THERMAL EFFECTS OF THE ACTION OF A GIANT LASER IMPULSE ON THE SURFACE OF OPAQUE SOLID BODIES

by

Roman Domanski

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EDITED TRANSLATION

FTD-ID(RS)T-1069-82 22 October 1982

MICROFICHE NR: FTD-82-C-001359

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English pages: 19

Source: Archiwum Termodynamiki, Vol. 2, Nr. 1, 1981, pp. 17-30

Country of origin: Poland
Translated by: SCITRAN
F33657-81-D-0263
Requester: FTD/TQTD
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STUDY OF THERMAL EFFECTS OF THE ACTION OF A GIANT LASER IMPULSE ON THE SURFACE OF OPAQUE SOLID BODIES

Roman Domanski
The Warsaw Polytechnic Institute, Warsaw

This paper presents results of studies concerning the duration time, size, rate of disappearance and temperature of plasma cloud which is formed in front of surface of an opaque solid body when this surface is struck by an impulse of laser radiation of high power. These results are utilized to verify the boundary conditions of heat transfer in cases of the impulse type input of energy to solid bodies.

Notation

a^* - ratio of energy absorbed by the sample to the sum of energy absorbed by the plasma and the sample
d_f - diameter of area subjected to laser radiation, mm
$\dot{E}$ - intensity of laser radiation, W/m^2
f - focal length of lens or optical system, mm
k - real speed of filming, frames/s
R - reflectivity of radiation
T - temperature, K
v - speed of movement of film tape, m/s
V - volume of shining part of cloud, mm^3
z - linear coordinate, m
ε - emissivity of solid body
ε_p - emissivity of plasma
λ - thermal conductivity, W/mK
λ - wavelength of radiation, μm
τ - time, s
τ_o - duration time of plasma cloud.

Introduction

Typical giant laser impulses enable to obtain the radiation intensity from 10^{10} to 10^{17} W/m^2, and their duration times are from 10^{-11} to $2 \cdot 10^{-7}$ s /1, 2, 3/. A number of varied physical phenomena occur when impulses of this type act on the surface of a solid body. In spite of many studies in this area these problems are still not well known because of their complexity. Thermal action of a giant laser impulse on a solid body appears to be of particular interest because of large possibilities of the application of sources of this type for drilling holes, cutting, welding and heating. Lasers of giant power find also application in medicine and in science (studies of nuclear fusion).

From the point of view of heat transfer (hence temperature distribution in material subjected to laser impulse of high power) it is essential to determine conditions of heat exchange at the surface of material, and the amount of heat conducted inside of the material /4, 5, 6, 7, 8/. In papers /1, 2, 9/ much information is given concerning the rate of growth of plasma cloud, and emission of ions and particles for a body subjected to the action of laser impulse, in the time of forming and lasting of impulse. There is shortage, however, of data about the time of duration of plasma cloud, and the rate of disappearance of shining cloud, although it was stated /1/ that for beams $E \geqslant 10^{12}$ W/m^2 this cloud may last much longer after the termination of impulse. This information is particularly important from the point of view of heat transfer between the cloud and the solid body.

The described studies (which formed a part of broader experimental and theoretical investigations) aimed at obtaining this part of lacking information necessary for proper formulation of boundary conditions of heat transfer, for impulse-type supply of energy to a solid body, particularly after termination of the impulse.

1. Description of test stand

An original test stand was set up for conducting studies. It consisted of neodymium laser and giant impulse, power supply system, a chamber with the sample, and system for photographing the phenomenon.

1.1. Source of giant thermal impulses

The laser used for studies was a neodymium laser with wavelength of emitted radiation $\lambda = 1.06$ μm, and diameter of beam in outlet mirror 8.2 mm. At the supply potential ~ 4 kV and capacity of the battery of condensers 400 μF, this laser could provide the peak power 50 MW and duration time of impulse of the order of 100 ns, at the laser control head (as stated by the producer - the Institute of Electronic Technology at the Warsaw Polytechnic Institute). These work parameters were obtained by piling the impulse to giant size by means of a prism rotating with velocity 38,000 rpm. In the case of not controlled work, the time of normal impulse was 2 ms.

Power supplier to the control head, with regulated supply potential and possibility of changing the capacity of battery, was made at the Institute of Thermal Technology with cooperation of the author.

The laser head, together with the control system and /19
power supply system, were placed in a screened cupboard (Figure 1).

1.2. Chamber with sample

The closed chamber (seen on the photograph) was placed on the optical bench on the axis of optical system of the laser outside the screened cupboard. The chamber was lined with black velvet to prevent reflection of the light. Condensing lenses were put on the axis of optical system before the inlet opening of the chamber.

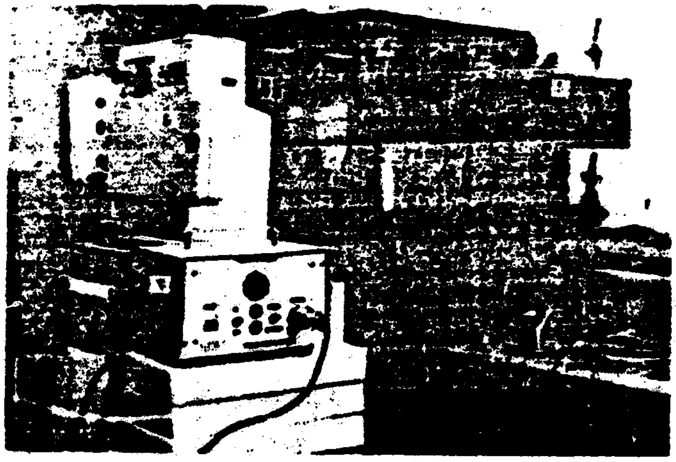

Figure 1. View of the test stand during filming with a Hyspeed camera

Inside the chamber, a sample of investigated material with thermal shields was placed on a moveable table with clamp and micrometer screw. The whole chamber could be moved on the optical bench, and more accurate changes in the location of sample could be made moving the table by means of the micrometer screw. At the constant location of the condensing lens, this arrangement allowed to change the intensity of radiation falling on the sample.

An opening was made in the chamber perpendicularly to the optical axis of the laser system; this hole enabled to take photographs of the area before the surface of the sample.

1.3. System for photographing effects of the action of laser radiation on surface of a solid body

In the course of studies, both static photographs of

the phenomenon and films with fast camera were made. Photographic camera was placed perpendicularly to the optical axis of the laser system in such a way that the front of the sample was parallel to the optical axis of the camera and the plane of the front of sample went through the axis of the camera. Static photographs were taken in complete darkness using both black and white and also color films. The aperture of the camera was opened and the laser system was turned on; photographs obtained /2
in this way for various materials are shown in further part of this work.

These photographs and conclusions derived from them formed the basis for introduction of a fast camera which would enable to obtain information about changes in plasma cloud as a function of time. A number of filming tests were carried out and finally it was decided to use for studies the camera HYSPEED H10/16 (producer: John Hadland, Photographic Instrumentation Ltd, Newhouse Laboratories) with maximum filming speed of 7000 frames/s. This camera had a double time marker - an automatic delaying system and an electronic control of frames with accuracy ± 1% at all speeds.

The test stand with the camera and equipment is shown in Figures 1 and 2. The filming was carried out using a Marco-Yvar teleobjective with focal length f = 150 mm.

2. Experimental results

Static photographs, black and white and in color, were taken to get information about the energy of laser impulse and its repeatability. Measurement of the energy of impulse is, in principle, a separate problem and it poses many technical difficulties. A series of attempts to measure this energy were carried out, since the manufacturer had no system to measure this energy, and its knowledge, at least estimated but based

Figure 2. Test stand with the chamber containing a sample: 1 - laser head, 2 - control system of the head, 3 - power supply, 4 - screened cupboard, 5 - chamber with sample, 6 - camera with delaying and controlling system, 7 - generator of time marking

on measurements, is essential in experimental and theoretical investigations. Results of studies of the energy of impulse, carried out by the author, are presented and discussed in the work /10/.

The first criterion allowing to estimate the power of impulse was to obtain piercing discharge in air at atmospheric pressure and humidity 55%. Such a discharge is shown in Figure 3. The length of spark was 9 mm, the focal length of lens f = 53 mm, the picture was taken on film ORWO 27 DIN. Seeing such a strong discharge we can conclude, on the basis of works /1, 5/, that for duration times of impulse of the order of 100 ns the peak power should be more than 25 MW. /2

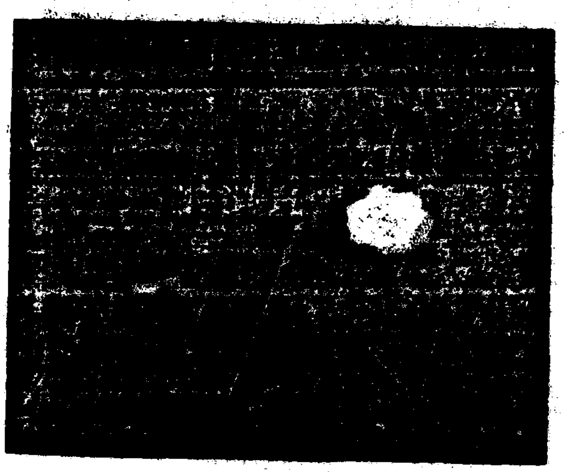

Figure 3. Sparking discharge in air caused by condensed beam of laser radiation

As an example, Figure 4 shows the action of laser impulse on the surface of ebonite. The dimension scale is shown on the photograph. As is seen, the shining cloud and particles of burning material reach the distance 23.8 mm, and the volume of the shining part of cloud is about 890 mm^3. Figure 5 shows a static photograph (open aperture) of plasma cloud ejected from the surface of copper. The diameter of irradiated surface is about 3 mm, and the focal length of condensing lens is 53 mm. Average density of energy absorbed in the sample and the cloud for these samples is ~ $1.5 \cdot 10^5$ J/m^2 (and the average density of power is $1.5 \cdot 10^{12}$ W/m^2) /10/.

On the basis of a series of photographs obtained in this way and studies of the temperature distribution in the sample /10/ the conclusion was reached that, despite maintaining constancy of the parameters of the power supplier at 4000 ± 30 V, no reproducibility of the energy impulse is obtained.

In the case of fil·ing, th· phenomenon was set out automatically: the control sy·te· of laser head was connected

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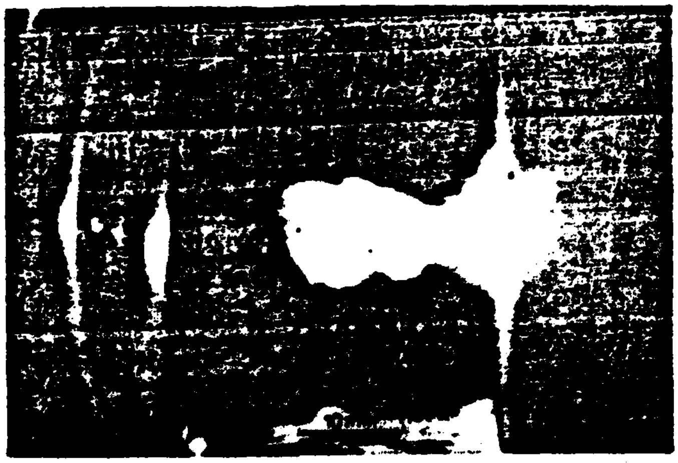

Figure 4. The action of a giant impulse of laser radiation on the surface of ebonite

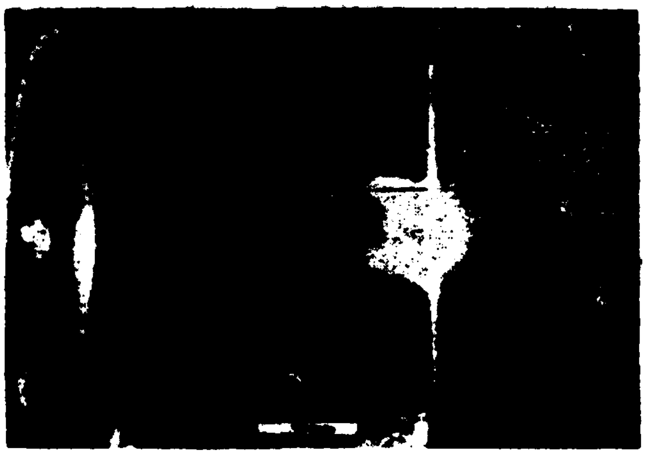

Figure 5. The action of a giant impulse of laser radiation on the surface of copper

to the delaying system of the camera which, after reaching a certain defined speed of filming, released the laser flash. Filming was done at the settings 4 and 5.6 on black-and-white film ORWO NP7 and on color film AGFA-Gevaert Type 605 Gevachrome Original High Speed with sensitivity 19 DIN (64 ASA) in daylight and 22 DIN (125 ASA) in artificial light. In the course of studies several series of films were made for various materials, different beam densities and different speeds of filming. /2

The composite photograph - Figure 6 - shows results of the action of laser radiation of high power on the surface of ebonite (rubber crosslinked with sulfur, 30% sulfur and the rest carbon and hydrogen). There are no points of time markers on the photographs, hence the time axes and the real filming speeds k [frames/s] and rates of the movement of tape v [m/s] are shown under each picture. By τ_* [s] we denoted the duration time of shining cloud counted on the basis of negatives. And thus, for picture 6c $\tau_* = 1.605 \cdot 10^{-3}$, since we added one frame in front which was totally overexposed and it was not worth showing it on the picture. All time measurements made in this work are based directly on time markers on negatives. As is seen from Figure 6, an increase of the energy density (by two-fold reduction of the laser beam area) results in more than two-fold increase of the duration time of shining cloud and increase of its volume. Figures 6b and 6c show that at a sufficiently large energy density the cloud can separate into several parts. The main part together with torn out and burning particles separates from the surface, and at the surface remains a cloud of shining particles on edges of the laser beam mark. This arises, it appears, from

burning of the edge of crater. Because of the fact that more than 70% of sample consists of carbon and hydrogen and remaining part of sulfur, we have here the combustion of material. The filming shows that the cloud reaches its maximum size in time many times shorter than the time of movement of one frame /2

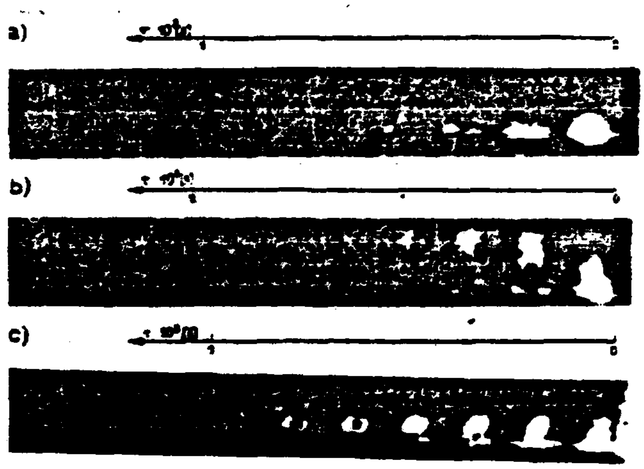

Figure 6. The action of laser radiation of great power at various radiation intensities on the surface of ebonite

	a)	b)	c)
d_f [mm] =	2.8	2.05	1.9
v [m/s] =	50.5	26	51.5
k [kl/s] =	6733	3466.6	6866.6
τ_0 [s] =	$0.725 \cdot 10^{-3}$	$1.7307 \cdot 10^{-3}$	$1.605 \cdot 10^{-3}$

(for the fastest rate), i.e., shorter than 0.14 ms; hence its rate of growth is very high and, defined as the speed of movement of shining front in the direction perpendicular to the surface of sample, for ebonite it is $\gg 10^3$ m/s. The rate of disappearance of shining cloud (counted on the basis of changes with time of the substitute diameter calculated from the volume of the shining part of cloud) is considerably smaller and for ebonite it is 7.8-16.1 m/s. Figure 8 shows changes of the volume of shining cloud, on the basis of Figure 6, as a function of time for various energy densities defined by the diameter of striking laser beam. The presented graphs should be treated as approximate only, since they were prepared on the basis of two-dimensional

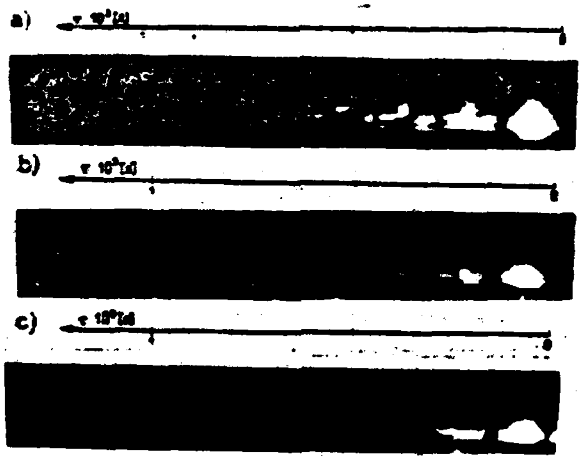

Figure 7. Changes with time of a shining cloud formed as a result of action of laser impulse of high power, at various radiation intensities, on the surface of copper

	a)	b)	c)
d_f [mm] =	2.5	1.35	1.2
v [m/s] =	50.5	49.3	49.5
k [kl/s] =	6733	6573	6600
τ_0 [s] =	$0.891 \cdot 10^{-3}$	$0.456 \cdot 10^{-3}$	$0.454 \cdot 10^{-3}$

photographs, and for some times it was problematic to determine the boundary, hence the volume of shining cloud. It can be concluded, however, that about two-fold increase of the density of beam at the level of the order of $1.5 \cdot 10^{12}$ W/m^2 causes nearly twice increase of the shining part of cloud. At the same time, it is necessary to admit that for times of the order of 0.5 ms the errors in calculating the volume may reach up to ± 20%.

Figure 7 shows selected pictures of plasma cloud arising as a result of action of a giant impulse on the surface of copper. The duration times of shining cloud for copper are in the range

from $0.89 \cdot 10^{-3}$ to $0.454 \cdot 10^{-3}$ s, and, as is seen on the presented pictures, an increase of the energy density of striking beam does not cause an increase of this time, and for larger densities of striking energy the time of shining decreases. Assuming that the total energy absorbed in the sample (of copper) and in the cloud is 1.1 J, one can determine from pictures (Figures 7a, 7b and 7c) the density of striking energy and the density of power. Correspondingly these values are $2.24 \cdot 10^{12}$ W/m^2, $7.68 \cdot 10^{12}$ W/m^2 and $9.73 \cdot 10^{12}$ W/m^2 assuming that the duration time of impulse is $\tau_i = 10^{-7}$ s.

On the basis of taken photographs (Figure 7) it is possible, as in the case of ebonite, to determine the rate of growth of shining cloud as defined previously; it is $\gg 54$ m/s. Also, it is possible to establish the rate of disappearance of plasma cloud; it is 9.4-26 m/s. Figure 9 shows changes of the volume of shining cloud torn from the surface of copper as a function of time, for various values of the energy density (different d_f) .These curves should be also treated as approximate only, since calculation of volume is burdened with considerable errors; moreover, for instance, in Figure 7a on the third frame a part of shining cloud reaches the edge of frame. The curves were drawn considering the fact that for $\tau = 0$, $V = 0$; also, for $\tau > \tau_w$ $V = 0$; hence in practice we had five points, which allowed to determine the character of curves. As is seen, for copper an increase of energy density from $2.22 \cdot 10^5$ J/m^2 to $9.71 \cdot 10^5$ J/m^2 causes an increase of the volume of cloud for the time $\sim 1.5 \cdot 10^{-4}$ s, but at lower energy densities the maximum of the cloud volume is shifted in the direction of longer times. During calculations of the volume of shining cloud on the basis of Figure 7 the part of shining field lying outside the edge of sample was rejected since it was only a reflection of light from the surface of sample.
As is seen, the plasma cloud derived from copper breaks in time into several elements. Part of them moves up and down the surface of sample (in Figures 7a and 7c it even goes outside the field

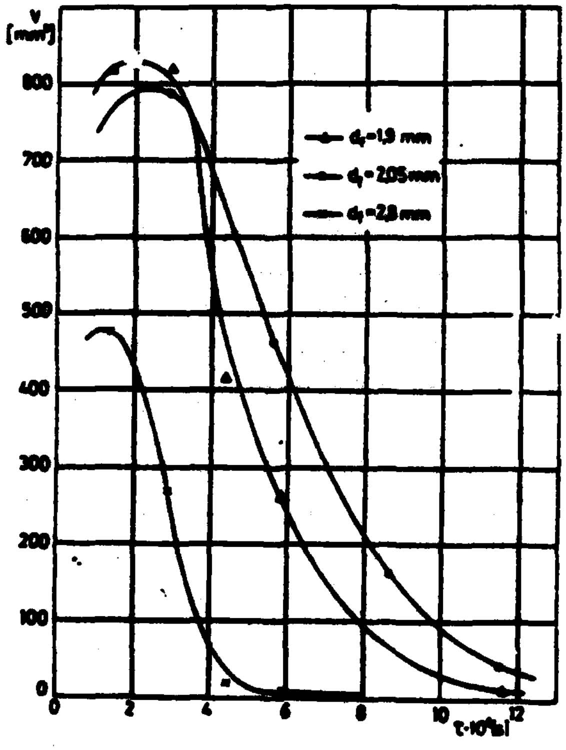

Figure 8. Changes of the volume of shining cloud ejected from the surface of ebonite as a function of time (on the basis of Figure 6) for various intensities of radiation (various values of laser beam diameter d_f)

of film frame), and also to the right and the left ., and one element perpendicularly to the surface of sample. A characteristic feature for copper is the appearance on pictures of a kind of shining branches (outflows) which evidence, as can be supposed, intensive movement of plasma inside the cloud, burning of particles and high pressures causing the outthrow of the groups of particles from the area of cloud.

On the basis of measurements of the loss of mass from the sample and of the volume of shining cloud one can calculate average specific gravity of the cloud. The value of density varies in the range from 0.28 kg/m^3 to 0.16 kg/m^3 for particular pictures in Figure 7, and was calculated after the time of about $1.5 \cdot 10^{-4}$ s from the moment of the start of impulse, that is from

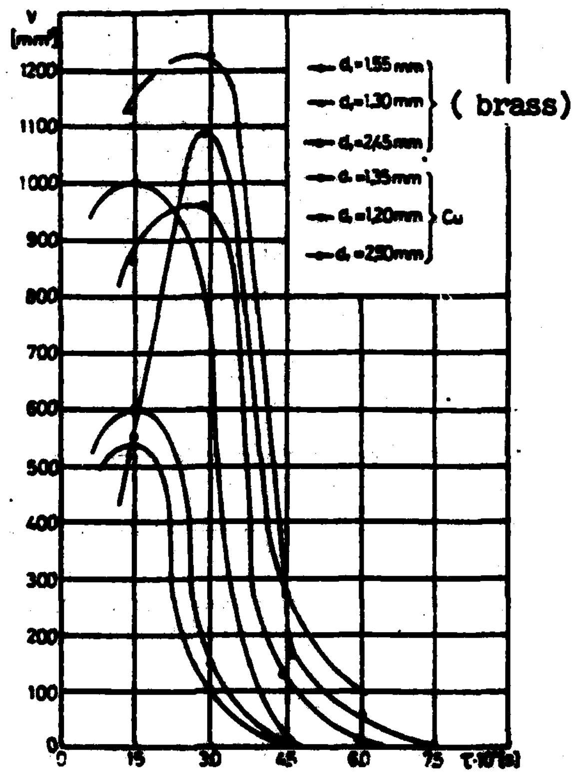

Figure 9. Changes of the volume of shining cloud ejected from the surface of copper (Figure 7) and of brass as a function of time for various intensities of energy (various values of laser beam diameter 4)

the first film frame.

It is possible to estimate the temperatures inside the cloud near its surface and their changes with time from films on color tape. On the basis of original film with known spectral sensitivity it was established that, for the time of the order of 0.14 ms, the inside part of cloud has white color, which corresponds to the temperature of the order of 5800 K. /2

The red color (650 $< \lambda <$ 600 nm) appears only after the time of about 0.42 ms, hence the temperature of cloud is

then in the region 4458 - 4829 K (according to Wien's Law). On the basis of these considerations we can assume that temperatures inside the shining cloud are of the order of 4500 - 5800 K; hence they are decidedly higher than the vaporization temperature of the material. The energy contained in the cloud is, therefore, higher than that calculated previously (for the temperature of vaporization), hence the average power of laser is greater than 22 MW.

Similar investigations were also carried out for brass and black rubber. They will not be described here because of the limited volume of this work. However, Figure 9 shows also changes in the volume of shining cloud for brass.

3. Conclusions from the conducted experimental studies

1. It was established on the basis of experiments that a stream of thermal energy provided to a solid body in the form of a giant impulse from neodymium laser, and falling on surface smaller than 10 mm^2, causes melting, vaporization and tearing off of particles of the material. These particles burn in air and form a cloud before the surface of the sample. Experiments show that the time of growth of the cloud is decidedly shorter than 0.14 ms, and its volume varies from 300 to 1200 mm^3, depending on density of falling energy and the kind of material of the sample.

2. The rate of disappearance of shining cloud, established on the basis of filming and time markers, is 9.4 - 26 m/s for copper, about 47 m/s for brass, and 7.8 - 16.1 m/s for ebonite.

3. On the basis of color photographs, static and taken with fast camera, and of the known spectral sensitivity, it was found that after the time 0.14 ms the temperatures inside the cloud may reach 5800 K, and after the time 0.5 ms for copper and brass they fall to the order of 4600 K.

4. The duration time of shining plasma cloud is of the order of 0.5 - 1.1 ms for metals, about 1.2 ms for ebonite, and is of the order of 4.5 ms for rubber (where particles continue burning in air). Hence, the shining plasma cloud exists for about 10^4 times longer than the duration time of laser impulse.

5. The energy contained in the cloud, estimated at 0.7 - 1.1 J (on assumption that the material evaporated but still has the temperature of vaporization), in reality is higher because of high temperature of the cloud /10/. Hence, the cloud can exchange heat with the sample long after termination of the /2
action of laser irradiation. Calculation of the amount of heat exchanged in this time (of the order of ms) would require a more accurate knowledge of changes of the cloud temperature, its emissivity, and thermal emissivity of the surface of sample and changes of its temperature. Moreover, calculations would require integration with respect to time. The fact that the radiation of vapors and gases does not obey the Stefan-Boltzman Law permits only an estimate of the amount of energy exchanged by radiation between the sample and the cloud. Assuming that the duration time of cloud is 1 ms, emissivity of plasma $\varepsilon_p = 0.8$, emissivity of molten copper $\varepsilon = 0.13$, temperature of plasma of the order of 3500 K, temperature of copper 1800 K, and taking the configuration coefficient as for two circular disks with diameters 8 mm for plasma and 6 mm for sample, the estimated amount of exchanged energy is about 0.086 J. The assumed conditions are, as it appears, very advantageous for transfer of energy to the sample, and yet this energy amounts to only about 10% of the energy stored in the cloud.

It can be assumed that, in reality, this energy exchange will be smaller and will form less than 50% of the energy absorbed by the sample. These are only guesses because of the lack of data.

6. During studies there was lack of reproducibility of the impulse, despite maintaining constant the conditions of work of the laser.

7. It follows clearly from the conducted studies concerning the energy absorbed by the sample and the plasma cloud that the main part of the energy of radiation remains in the cloud. During its formation (the rate of growth is of the order of 10^4 m/s /1, 5/) the amount of energy reaching the surface of the sample is reduced considerably in relation to the emitted energy. This should find its expression in the formulation of boundary conditions. A correction should be introduced which would consider the division of absorbed energy between the sample and the cloud, irrespective of changes of reflexivity of the surface of sample. It appears that this could be expressed in the following way

$$-\lambda \frac{\partial T}{\partial z}\bigg|_{z=0} = E(\tau)\,[1-R(\tau)]\,a^{*},$$

where a^{*} is the ratio of energy absorbed by the sample to the sum of energy absorbed by the sample and the cloud and should be determined depending on the kind of sample material and the intensity of falling radiation. For the case considered in this work, for metals, the amount of energy absorbed in the sample with occurrence of vaporization was about 10% of the energy absorbed in the sample and the cloud, hence we had the value $a^{*} \approx 0.1$.

After termination of impulse, it should be necessary for a given material (depending on the amount of energy contained in the sample and the cloud) to consider the distribution of temperature (calculated from the wave equation or diffusion equation depending on the duration time of impulse and relaxation

time) in the sample with consideration of the heat exchange from the surface $z = 0$, hence also of the heat exchange with the cloud existing for a few miliseconds. /2

Final remarks

The described studies of the action of laser impulse on the surface of solid bodies concern exclusively the area in front of the surface of sample , and they form only a part of studies in this field carried out at the Institute of Thermal Technology. The energy of laser impulse was also studied, and application limits for Fourier heat conduction equation and equation of hyperbolic type were established /11/. There are great experimental difficulties in the work involving times from 10^{-7} s to 10^{-3} s and power density of the order of 10^{12} W/m^2 and higher. Nevertheless it appears that these studies allowed to draw certain important conclusions concerning the formulation of boundary conditions of heat exchange when calculating temperature fields in bodies subjected to the action of heat impulse of high power.

Manuscript received by the Editor
in June 1980

Investigation on thermal effects of the giant laser pulse stroke at the opaque solid target /30

Summary

The paper presents some experimental results concerning the duration time, volume and time periods for plasma to form and vanish when the giant laser beam strokes at the opaque surface. These results have been used to verify the boundary conditions of heat transfer in the cases of energy pulse absorption by the solid target.

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